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Case studies and testing of the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009

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Case Study – A thorium source in the Mountain Pass rare earth elements deposit, California, United States, and the application of UNFC-2009

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I. Introduction

1. Historically, uranium and thorium deposits worldwide have been classified and reported according to the resource reporting scheme developed by the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (NEA) and the International Atomic Energy Agency (IAEA). This system consists of a biaxial classification that considers the degree of geological knowledge and the production costs of uranium concentrate and (where applicable) thorium concentrate.

2. Thorium, similar to uranium, can be utilized as a nuclear fuel. Despite numerous projects and several pilot test reactors in several countries designed to evaluate thorium as a viable reactor fuel, thorium-based nuclear power has yet to be fully commercialized. Currently, research and development is being carried out on several concepts for advanced reactors including: high-temperature gas-cooled reactors (HTGR); molten salt reactors (MSR); Canada Deuterium Uranium (CANDU)-type reactors; advanced heavy water

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reactors (AHWR); and fast breeder reactors (FBR). Federal government-supported projects, particularly in India and China, are focused on the development of thorium-based nuclear power [1]. Based on these activities, utilization of thorium as a fuel is expected after 2020.

II. Background

3. Because of the low demand for thorium, it has not been a primary target of exploration in the past. The research and development efforts mentioned above may increase the demands for thorium and likewise increase national and global evaluations of thorium deposits.

4. Mineral deposits that are rich in the rare earth elements (REEs) typically also contain anomalous enrichments in thorium. Primarily for this reason, the most likely sources of thorium in the foreseeable future will come from the recovery of thorium as a co-product of the mining and processing of REE deposits.

5. Production of REEs during the 1950s to the late 1980s came primarily from the United States, India, South Africa and Brazil. In 1927, Chinese geologists discovered REE deposits at Bayan Obo in the Inner Mongolia Autonomous Region. Mines and processing plants built at Bayan Obo began to produce REE concentrates in 1957 [2]. By 2002, China became the dominant producer of REEs in the world [2]. During the more than 80 years following the discovery of Bayan Obo, REE deposits were found in 21 of China's Provinces and Autonomous Regions [2]. In 2009, China reported its domestic extractable quantities of REEs as 18.6 million metric tons (tonnes) of REE oxide [3, p. 410]. China introduced a production quota on its REE industry in 2008 [2], which triggered a worldwide search for REE deposits in other countries. In recent years, deposits of REE resources have been assessed in Australia, Brazil, Canada, China, Finland, Greenland, India, Kyrgyzstan, Madagascar, Malawi, Mozambique, South Africa, Sweden, Tanzania, Turkey, the United States, and Vietnam [4, 5, 6].

6. Actively mined REE ore deposits are economic on the basis of their REE production. Co-existing thorium-rich minerals could be evaluated as sources of by-product or co-product thorium if a market develops for thorium in the future. For now, the production of thorium as the primary product is thought to be uneconomic [1]. In the context of production, a by-product can be defined as the "output from a joint production process that is minor in quantity and/or net realizable value (NVR) when compared to the main products" [7]. By convention, by-products also are not inventoried, but the NRV from by-products is typically recognized as 'other income' or as a reduction of joint production processing costs when the by-product is produced. Co-product on the other hand is a major output from a joint production process that is significant in quantity and/or NVR. Co-products play an important role in the economic analysis of a mineral project.

7. In most REE-thorium-rich deposits, the most common thorium-bearing mineral is monazite, an REE-thorium-phosphate mineral. Thus, most of the thorium content in the majority of REE deposits is due to monazite and only occasionally due to other thorium-rich minerals, such as thorite (thorium silicate). Monazite can contain as much as 20 per cent thorium oxide [8]; hence, thorium may be evaluated as a co-product in many REE deposits containing monazite.

8. Moreover, policy objectives of waste hierarchy, such as the European Union Waste Framework Directive (established in 1975), mandate disposal as the last and least desirable of the management options of any process residues [9, 10]. Reuse, recycling, energy recovery, and other potential uses are to be considered before materials are assigned as waste and presumptively disposed.

9. Monazite concentrate production is currently taking place in India, Malaysia, Vietnam, and Brazil, in decreasing order of production [4]. The Indian Bureau of Mines describes India's coordinated effort to recover monazite from heavy-mineral sands then chemically treat the monazite to separate rare earths in composite chloride form and thorium as hydroxide upgrade [11]. The planned capacity of the monazite processing plant was established at 10,000 tonnes per year in 2011, expected to be increased to 20,000 tonnes per year in the future [11]. The recovery of thorium from monazite-rich ore is being considered for the Steenkampskraal deposit in South Africa, which is an REE mining and production project under development in 2014 [12, 13].

10. The co-product occurrence of thorium and a general lack of economic interest in thorium have meant that thorium quantities were rarely, if ever, accurately defined in most countries. Information on estimated quantities of thorium was published between 1965 and 1981 in the biennial publication the "Red Book", published jointly by the NEA and IAEA; the thorium estimates reported in these reports applied the same terminology as was used for uranium resources at that time. The "Red Book" is the informal, commonly used name for a biennial report prepared jointly by the NEA and IAEA [1], which provides the most recent overview of the world uranium market fundamentals and industry, including uranium exploration, resources, production, and projected reactor-related requirements.

11. In 2012, the United States reported identified domestic thorium quantities (in situ) of about 434,000 tonnes of thorium [1]. The principal thorium deposit types in the United States are vein-type, carbonatite-hosted, and placers [14].

III. The Case Study

12. The United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) allows the documentation and reporting of estimated known, inferred, and undiscovered thorium quantities. The UNFC-2009 classification scheme, in addition to providing the project maturity of mineral commodities, considers social and economic issues, including regulatory, legal and market conditions imposed by governments and markets, domestic demand, technological and industrial progress, as well as ever-present uncertainty of the foreseeable future.

13. This case study presented here is a UNFC-2009 classification of a REE-thorium deposit in California, United States, classifying the deposit as both a source of REEs and as a potential source of thorium. Specifically, the deposit used in this example is the REE ore body developed by the Mountain Pass mine in southeast California, owned and operated by Molycorp Inc.¹ (Figure 1). The mine and onsite mineral processing plants exploit the largest known REE deposit in the United States—the Sulphide Queen carbonatite [15]. After an eight-year hiatus, Molycorp reopened operations at the mine in late 2010. The mining and ore-processing operations at Mountain Pass remain active at this time (2014).

14. The REE ore body of Mountain Pass represents a potential future source of thorium as a co-product of REE production. The thorium content in this ore body is primarily due to the mineral monazite, which is intimately intergrown with the REE ore minerals. Monazite concentrations range throughout the ore body from trace amounts to locally abundant [15].

15. Molycorp Inc. reports that the Mountain Pass ore body—the Sulphide Queen carbonatite—contains Proven and Probable Reserves of 16.7 million tonnes of ore with an average grade of 7.98 per cent REE oxides, applying a cut-off grade of 5 per cent REE oxides [16]. A recent United States Geological Survey reconnaissance bulk sampling of ore

¹ <http://www.molycorp.com/>

exposed in the open-pit mine (about one tonne of composited ore was collected) found an average thorium content of approximately 0.025 per cent within high-grade REE ore; this value is nearly identical to the thorium concentrations found in earlier geochemical studies of this carbonatite [17]. This thorium concentration suggests that each tonne of ore mined from the deposit contains on average approximately 0.25 kilogrammes of thorium. This estimate of thorium content in the Sulphide Queen orebody is certainly an approximation based on limited sampling; monazite concentrations may prove to vary considerably across the carbonatite ore body as mining progresses. For discussion purposes, applying an ore body estimated to comprise at least 16.7 million tonnes of carbonatite, with an average thorium content of about 0.025 per cent, there would be an estimated resource of at least 4,200 tonnes of thorium at Mountain Pass. Since the estimates are based on limited sampling and extrapolation, it should be considered as an estimate in the lowest level of geological confidence.

16. The mining and processing operation at Mountain Pass is currently devoted only to the recovery and separation of REEs. No plans have been reported by the company to recover the thorium in the foreseeable future. At this time (2015), when the carbonatite of Mountain Pass is mined, processed, and the REEs are separated, the thorium moves with other residues into the tailings impoundment. Thus, it would require modification of the process flow-sheet and/or further reprocessing of the tailings in order to recover the thorium in the future.

IV. Classification of the case study by UNFC-2009

17. As a mine and production operation for REEs, the Mountain Pass mine of Molycorp would be classified using UNFC-2009 as E1.1 F1.1 G1.2. That is, on its basis as a rare earth element operation, it is classified by these categories and sub-categories (Table 1):

- **E1.1** "Extraction and sale is economic on the basis of current market conditions and realistic assumptions of future market conditions."
- **F1.1** "Extraction is currently taking place."
- **G1, G2** "Quantities associated with a known deposit that can be estimated with a high level of confidence" (Proven Reserves) and "with moderate level of confidence" (Probable Reserves).

18. In contrast, viewed additionally as a known, unutilized thorium deposit sampled for thorium content at a reconnaissance level, this mineral deposit may be classified as E3.3 F2.3 G3:

- **E3.3** "On the basis of realistic assumptions of future market conditions, it is currently considered that there are not reasonable prospects for economic prospects for economic extraction and sale in the foreseeable future."
- **F2.3** "There are no current plans to develop or to acquire additional data at the time due to limited potential."
- **G3** "Quantities [of thorium] associated with a known deposit that can be estimated with a low level of confidence."

Figure 1.

The Mountain Pass mine of Molycorp, Inc. in Southeast California. This is the only active REE mine in the United States (in 2015). The ore body is a carbonatite intrusion, thought to represent the largest REE resource in the United States (Photograph by B. Van Gosen, USGS)



Table 1.

REE and thorium resources of the Mountain Pass deposit, California, classified in UNFC-2009 scheme

Mountain Pass deposit	Quantities (tonnes)	Average Grade (%)	CRIRSCO Classification	UNFC-2009 Categories			UNFC-2009 Class	UNFC-2009 Sub-Class
				E	F	G		
Total REE oxides	1 333 000 ^a	7.98 (as oxide)	Proven + Probable Reserves	1.1	1.1	1.2	Commercial Project	On Production
Thorium	4 200	0.025 (elemental weight %)	Inventory ^b	3.3	2.3	3	Non-Commercial Project	Development Not Viable

^a Proven and probable REE reserves based on an estimated 16,700,000 tonnes of carbonatite ore (grades and tonnages for the REE reserves categories are combined in the public reporting).

^b Not defined in the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) Template.

IV. Conclusion

19. The application of UNFC-2009 as a complement to the NEA/IAEA Classification contributes to both a better understanding of the availability of thorium in the United States as well as providing information on how these sources may contribute to future planning and enactment of nuclear energy programmes.

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